AD-A112 893   GEORGIA INST OF TECH ATLANTA PRODUCTION AND DISTRIBU--ETC F/G 15/5
              MATERIAL HANDLING: A REVIEW.(U)
              MAR 82   J O MATSON, J A WHITE   N00014-80-K-0709
UNCLASSIFIED PDRC-82-04   NL
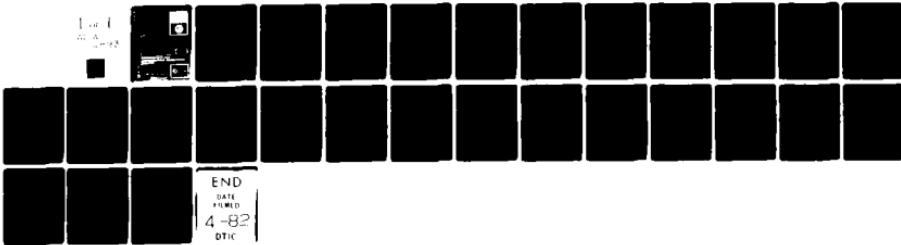
END
DATE
FILMED
4-82
DTIC

MICROCOPY RESOLUTION TEST CHART
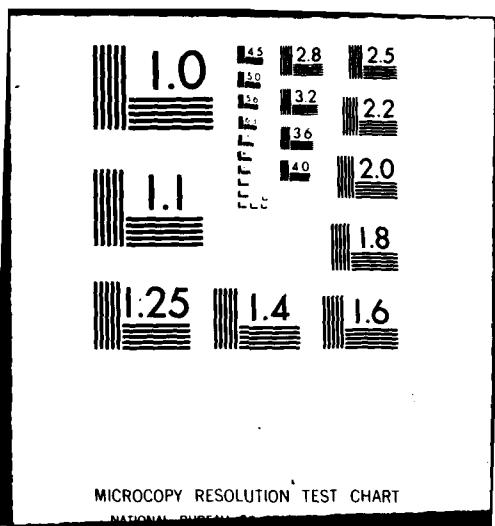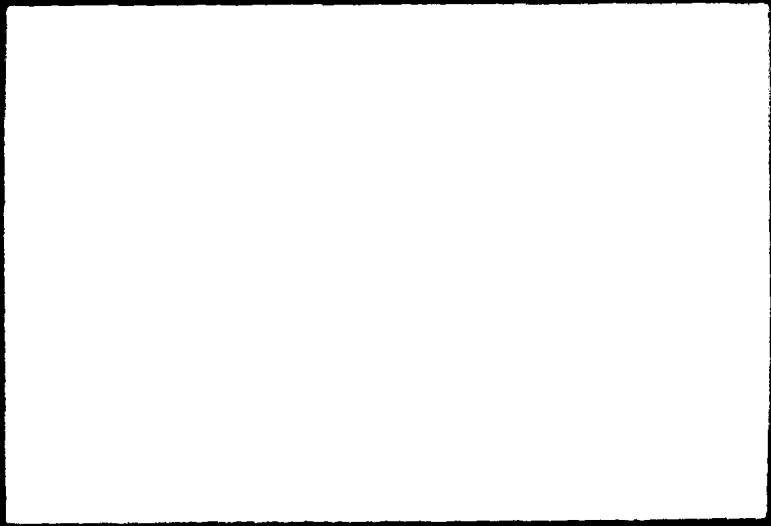
(12)

MATERIAL HANDLING: A REVIEW

by

Jessica O. Matson[†]
John A. White[†]

PDRC 82-04

[†]School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, Georgia
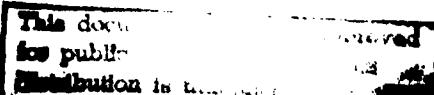
MATERIAL HANDLING: A REVIEW[1]

Jessica O. Matson
John A. White

School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, Georgia U.S.A.

ABSTRACT

A number of material handling research areas are reviewed
and opportunities for further research are identified.
Included in the review is a consideration of the following
areas: robotics, conveyor theory, transfer lines, flexible
manufacturing systems, equipment selection, storage alter-
natives, automated storage and retrieval systems, warehouse
layout, palletizing, and order picking and accumulation.

1. INTRODUCTION

In recent years there has developed a body of operational research literature that could be loosely classified as material handling research. Because of the growing interest in both the _design_ of new or improved material handling systems and the _operation_ of existing systems, it seems appropriate and timely to provide an overview of the field and to focus on future research needs. Design issues typically are focused on _strategic_ aspects of the system; whereas, operational issues are generally focused on _tactical_ aspects.

The increasing capability to utilize the computer to control material handling systems has resulted in a surge of interest in the general field of material handling. The microprocessor revolution has certainly made its mark on the field. The role and scope of material handling, as well as material handling technology, have undergone dramatic changes. Not many years ago, it seemed sufficient to define material handling as simply handling material. Today, material handling is defined much more broadly. As an example, one might define material handling as using the _right method_ to provide safely the _right amount_ of the _right material_ without damage at the _right place_, at the _right time_, in the _right condition_, and at the _right cost_.

Some continue to view material handling as "lift that barge and tote that bale". Others view material handling to be handling, storing, and controlling material, with considerable emphasis on the latter.

The Factory of the Future, also known as the automatic factory, has captured the attention of upper management in corporations throughout the world. The recent announcements from Japan's Fujitsu Fanuc and Yamazaki Machinery Works of unmanned factory systems, coupled with the broad application in Japan of quality circles, rapid tool setting, and "The Toyota Production System",

have generated intense pressures among the developed countries to reindustrialize and to design automated factory systems.

The emphasis on automated factory systems has focused considerable attention on the use of automated material handling systems. Unfortunately, the rush by industry to install automated equipment has resulted in the creation of _islands_ _of_ _automation_, rather than _integrated_ _material_ _handling_ _systems_.

Typical examples of islands of automation include numerically controlled machine tools, robots, automated storage/retrieval systems, automated guided vehicles, automatic palletizers, automatic tool changers, transfer lines, and flexible manufacturing systems. In some cases, the islands are the size of individual work stations or machine centers; in other cases, the islands are the size of manufacturing departments.

From a systems viewpoint, islands of automation are not necessarily bad, so long as they are considered to be interim objectives in a phased implementation of an automated system. However, to obtain an integrated factory system, the islands of automation must be tied together or linked. An obvious approach that can be used to physically bridge the islands of automation is the material handling system.

Very little basic research has been devoted to issues related to the design of _integrated_ material handling systems. Indeed, few have addressed the subject of material handling at all. Those who have studied explicitly material handling problems have tended to focus on a very narrowly defined aspect of the subject; counter-examples would include large scale simulation efforts.

Even though there has been a limited amount of research performed that addresses explicitly material handling problems, much of the research devoted to other, more generic, problems is applicable to material handling. Some

examples of research areas that realistically contribute to a better under-
standing of material handling problems include ergonomics, man-machine systems,
vehicle routing, facilities layout and location, scheduling and sequencing,
queueing theory, and computer storage systems design, among others. A brief
description of some of the generic research areas of operational research
that relate to material handling is given by Maxwell [37].

In this review paper, the coverage of operational research applied to
material handling is limited to the following ten categories: robotics, con-
veyor theory, transfer lines, flexible manufacturing systems, equipment se-
lection, storage alternatives, automated storage and retrieval systems, ware-
house layout, palletizing, and order picking and accumulation. It is empha-
sized that the set of ten categories does not represent a definition of ma-
terial handling; the set is neither exhaustive nor mutually exclusive.
Furthermore, the coverage of any specific category is not intended to be a
comprehensive survey of the literature.

The objective of the review is to acquaint the reader with the breadth
and depth of the research that has been devoted to material handling. Addi-
tionally, it is hoped that the review will stimulate additional research on
material handling problems.

Most of the research described in the review deals with the development
of analytical models of some aspect of material handling. Only a brief amount
of attention is given to the application of simulation in modeling material
handling systems. The imbalance in our coverage of simulation is due to our
belief that more research attention is needed in the development of analytical
models. There have been many very successful applications of simulation in
designing material handling systems, Phillips [45], Rearick, et al. [49], and
Swain and Marsh [59].

3

2. ROBOTICS

Robotic research has been directed toward either the design of robot hardware and/or software systems or the integration of a robot in a manufacturing or assembly environment. As examples, Medeiros, et al. [39] developed a simulation model for a manufacturing cell that included a robot with vision; the production setting was assumed to be low-volume, batch manufacturing. A detailed simulation model was developed by Stokić and Vukobratović [58] to study the insertion of a peg into a hole; the model included the consideration of manipulator dynamics during the assembly process; their analysis included trajectory control and feedback in the case of interference. Nof, et al. [44] studied the comparative abilities and limitations of industrial robots and humans; they developed a robot oriented job and skills analysis method to optimize the task performance for the robot and to aid in the selection of specific robots for specific tasks. Vereschagin and Generozov [61] used dynamic programming to determine the optimal trajectory of the robot arm in performing a given task.

3. CONVEYOR THEORY

In comparison with the other research categories, there exists a large literature devoted to conveyor theory. Muth and White [43] reviewed the conveyor theory literature through 1977; deterministic and probabilistic models of conveyors were considered, as well as descriptive and normative approaches to modeling conveyor systems. The review focused on the study of operational characteristics of conveyor systems. The state-of-the-art for conveyor theory research is perhaps best represented by the contributions of Muth [41], [42], Gregory and Litton [20], and Maxwell and Wilson [38].

Muth [41] developed a deterministic model of material flow on a conveyor having multiple loading and unloading stations, equally spaced carriers, and periodically time-varying patterns of material flow; the stations can perform either pure loading, pure unloading, or alternating loading and unloading operations. Material flow along the conveyor is described by a difference equation whose solution yields steady state conditions for general flow patterns.

In [42] Muth considered random material flow for a conveyor with discretely spaced carriers and having a single loading station and a single unloading station. He found that the conveyor could serve as a variance-reducer; however, to decrease the output variance required an increase in conveyor capacity.

Gregory and Litton [20] modeled probabilistically a conveyor with discretely spaced carriers serving multiple unloading stations; no recirculation of material was allowed. All carriers approaching the first station were assumed to be loaded with one unit. Times between successive unloading attempts are assumed to be exponentially distributed; if an unloading attempt is unsuccessful due to a carrier being empty, the operator waits for the next loaded carrier to arrive. (Subsequently, Ohta [45] developed a GERT network representation of the conveyor system studied by Gregory and Litton; Ohta's formulation allows the use of general probability distributions.)

Maxwell and Wilson [38] developed a network model of a conveyor system; they modeled the dynamic performance of the conveyor system by using a time expanded network flow model. Models were developed for a variety of conveyors and their results were compared with industrial practice.

4. TRANSFER LINES

A transfer line consists of several machines linked together in series by a conveyor; buffer storage is frequently provided between the machines. Transfer lines are typically modeled as a series of queues.

Research on transfer lines can be classified using the following criteria:

1. Processing Times

    a. Constant

    b. Random

2. Machine Failures

    a. Do Not Occur

    b. Occur Deterministically

    c. Occur Randomly

        i. Independently

        ii. Dependently

3. Machine Downtime Durations

    a. Zero

    b. Constant

    c. Random

4. Scrapping of Material Being Worked on

    When a Machine Fails

    a. None Scrapped

    b. All Scrapped

    c. Randomly Scrapped

5. Buffer Storage Capacities

    a. Zero

    b. Finite

    c. Infinite

6. Inter-Arrival Times at First Machine

    a. Zero

    b. Random

7. Material Flow

    a. Discrete

    b. Continuous

8. Method of Modeling

    a. Analytical

    b. Simulation

Relatively few of the possible combinations of the eight categories given above have been addressed. In general, the research performed on transfer lines having random components has assumed memoryless distributions or combinations of memoryless distributions.

The publications by Buzacott and Hanifin [10], Gershwin and Berman [15], and Ignall and Silver [26] are representative of the contributions to the research on transfer lines. Buzacott and Hanifin [10] evaluate and compare seven analytical models of transfer lines; they also compare the model results with real data from a transfer line. Gershwin and Berman [15] consider a transfer line for discrete parts consisting of two machines and a single finite buffer; exponential service, failure, and repair processes are assumed; they also provide an extensive listing of research papers treating analytical models of transfer lines. Ignall and Silver [26] consider a generalization of the transfer line that can be represented as a series of two multi-server queues; a two-stage system is considered, with multiple machines available at each stage; they estimate the output from the system as a function of the size of the inter-stage buffer.

7

5. FLEXIBLE MANUFACTURING SYSTEMS

Where transfer lines can be modeled as a series of work stations, a flexible manufacturing system can be represented as a network of work stations. The flexibility is obtained from the use of general purpose machines and a material handling system that allows multiple routings of material through the machines. Typically, the flexible manufacturing system is under central computer control. (Hutchinson and Wynne [25] provide a detailed description of flexible manufacturing systems.)

With a transfer line, all parts follow the same sequence of operations. When a machine fails, the transfer line is generally blocked. With a flexible manufacturing system, different material routings are achieved either by "providing separate flow paths between each pair of machines" or by "using a common material handling device through which all parts pass and which connects all machines". [11].

Buzacott and Shanthikumar [11] developed analytical models of a number of flexible manufacturing systems; they also considered a number of alternate storage and control alternatives. Based on their research, it was concluded that the effectiveness of the flexible manufacturing system is strongly dependent on the effectiveness of the control system.

In addition to the analytical models studied by Buzacott and Shanthikumar [11], a number of simulation models of flexible manufacturing systems have been developed. Hughes [24] describes a simulation model that is used by a flexible manufacturing system supplier in designing such systems. Biles and Yang [7] also developed a simulation model of flexible manufacturing systems; they focused on the material handling components, with specific attention given to the use of multiple parallel conveyors.

8

6. EQUIPMENT SELECTION

Several heuristic procedures have been developed for selecting the appropriate materials handling equipment from a large number of alternatives. Jones [27], for example, formulated the equipment selection problem as a network flow problem in which the nodes represented equipment alternatives for each warehousing function and the arcs represented the compatibility of equipment alternatives serving successive warehouse functions. His assumptions included specific equipment for each warehouse function, no mixed mode equipment selections for warehouse functions other than retrieval of goods from storage, no cost for goods' processing and waiting times, arrival and storage of goods in unitized form, and retrieval of goods by individual cartons. The solution procedure required determining the least-cost paths through separate receiving and shipping networks. Simulation was used for queuing investigations to develop approximations for parameters associated with throughput requirements.

Assuming a given set of moves, Webster and Reed [62] formulated the problem as an assignment problem and developed a solution procedure based on specification of a cost matrix for each move-equipment combination. The procedure consisted of two main steps: (1) determination of an initial feasible solution, and (2) improvement of the initial solution by considering system utilization. Combining the heuristic equipment selection procedure of Webster and Reed with the CRAFT facilities layout procedure [1], [9], Tompkins and Reed [60] developed the COFAD (COmputerized FAcilities Design) model. COFAD jointly selects the facility layout and materials handling equipment combination which minimizes material handling costs.

9

Graves and Whitney [19] examined the equipment (resource) selection and assignment problem in the context of assembly systems design. For a mixed-integer linear programming formulation of the problem, they proposed a branch and bound solution procedure in which bounds were determined by subgradient optimization. The solution procedure was demonstrated for the design of a robot assembly system. Graves and Lamar [18] extended the work of [19] and established a more general integer programming formulation. An approximate solution procedure which provided integer assignments was given.

7. STORAGE ALTERNATIVES

Examples of unit load storage alternatives include block stacking, pallet racks, and deep lane storage systems. Much of the research on the design and evaluation of these storage alternatives has been concentrated on the criterion of space utilization. Moder and Thornton [40], for example, developed quantitative models for block stacking to determine the effect of clearance between lanes and the angle of the storage lanes on space utilization, assuming maximum occupancy of the storage positions. Kind [30], [31] demonstrated that space utilization should be considered, not only at peak inventory, but over the entire inventory cycle of a product; he proposed a formula for block stacking lane depth which approximately maximized space utilization for a product whose inventory cycle was characterized by uniform withdrawal of stock, instantaneous replenishment, and zero safety stock.

Kind's study [30] was the first of several to consider the design of storage systems for maximum space utilization over a product's inventory cycle, given the assumptions of randomized storage, FIFO lot rotation, and unit load storages and retrievals. Kooy [32], Kooy and Peterson [33], and DeMars [12]

10

reported on the solution of some actual storage design problems in industry. White, DeMars, and Matson [64] developed analytical models to determine the minimum space designs for block stacking, single-deep and double-deep pallet rack, deep lane storage, and unit load AR/RS. Three storage-retrieval distributions were considered including a uniform withdrawal rate, an increasing withdrawal rate, and a decreasing withdrawal rate. Extending the analysis of [64], Matson and White [35] demonstrated the effect of handling requirements on the optimum storage design and developed a total cost model for block stacking incorporating both space and throughput costs. In addition, block stacking models for products with bulk withdrawals were given. Matson, Shieh, and White [36] used a dynamic programming approach to determine the minimum space block stacking lane depths for the case of lot splitting. In addition, they considered the problem of determining the optimum lane depths for multiple products when there is a constraint on the number of depths allowed.

Using simulation, Marsh [34] compared three alternative policies for the operation of block stacking storage systems. He examined the effect on space utilization of storing in longer or shorter lanes when the optimum lane depth is not available.

8. AUTOMATED STORAGE/RETRIEVAL SYSTEMS

The design and operation of automated storage and retrieval systems have been studied by a number of researchers. Hausman, Schwarz, and Graves [21], Graves, Hausman, and Schwarz [17], and Schwarz, Graves, and Hausman [53] studied the assignment of multiple items to the same pallet, the assignment of pallet loads to storage locations, and the sequencing of storage and retrieval requests. They considered both dedicated (fixed-slot) storage and randomized (floating-slot) storage.

11

White and Bozer [63] extended the research of Graves, Hausman, and Schwarz to include economic considerations. Using cost estimates developed by Zollinger [66], an optimization model was developed to determine the number, length, and height of storage aisles to minimize the after-tax, present worth cost of the combination of storage racks, storage machines, building, and land.

Karasawa, Nakayama, and Dohi [29] developed a non-linear mixed integer programming formulation of an AS/RS. Their cost model also included consideration of storage racks, storage machines, building, and land. However, their model differed significantly from that developed by Zollinger [66].

Bozer, Shieh, and White [8] developed a procedure for determining travel time for both single command and dual command cycles for an AS/RS when horizontal and vertical travel occur simultaneously and the storage/retrieval horizontal and vertical addresses are independently distributed random variables. Additionally, they developed an interactive procedure for determining the dedicated storage assignment of pallets to storage slots to maximize throughput under single command and dual command conditions; a colorgraphics computer was used to display layout information to the user.

A number of analytical and simulation models have been developed by AS/RS equipment suppliers and user companies. Much of the work has focused on specific applications and design questions. Examples of such work include the efforts of Barrett [3] and Sand [51].

9. WAREHOUSE LAYOUT

The location of inventory items in the warehouse to minimize material handling time or costs is one aspect of the warehouse layout problem which has received much attention. Kallina and Lynn [28] discussed the application

12

of the cube-per-order index rule, first proposed by Heskett [22], for assigning warehouse space to inventory items. Francis and White [14] investigated both discrete and continuous layout problems and demonstrated that the cube-per-order rule minimizes handling costs when a "factoring" assumption is satisfied. A contour line solution procedure was given for continuous layout designs.

Employing the cube-per-order rule, Wilson [65] jointly considered the relationship of the stock location and order quantity problems. An iterative gradient search procedure was used to solve the nonlinear programming formulation. Whereas Wilson examined the discrete layout problem, Hodgson and Lowe [23] developed an algorithm to find locally minimum cost solutions for the continuous design problem.

Another element of warehouse layout involves determining the actual configuration of storage bays, aisles, and doors to minimize handling costs. Roberts and Reed [50] used dynamic programming to determine the optimum configuration of storage bays to minimize handling and construction costs. Their assumptions included the following: a single dock location, randomized storage, FIFO inventory policy, rectilinear travel, and storage bays of identical size and orientation. Bassan, Roll, and Rosenblatt [6] investigated the optimum number of racks or shelves, and the length of rack sections for two warehouse layout configurations; handling, floor space, and building perimeter costs were included in the analysis; and some rules were developed, based on cost ratios, regarding the preferred warehouse layout.

10. PALLETIZING

Palletization research has concentrated on three topics: (1) setting the optimum pallet size, (2) selecting the optimum pallet layout, and (3) scheduling the items to be palletized. Steudel [56] considered the effect of pallet size

13

on materials handling, storage system, and floor space costs. To determine
the optimum pallet size, he developed a computer model to determine the op-
timum pallet layout and to evaluate a total cost function for each alternative
pallet size.

Steudel [57] also examined the pallet loading problem as a special case
of the two-dimensional cutting stock problem. Assuming that all rectangles
were of equal size and allowing nonguillotine cuts, he proposed a heuristic
procedure based on dynamic programming. The heuristic, which provided a
cyclic four module layout pattern, first maximizes utilization of the pallet
perimeter and then projected the perimeter arrangement inward toward the pal-
let center. Correction steps were required for overlapping rectangles and
large central holes.

Others who have proposed pallet layout heuristics for similar assumptions
include Smith and DeCani [55] and Ratliff and Tran [48]. Smith and DeCani
described the implementation of an enumerative procedure to evaluate all pos-
sible cyclic layouts. Ratliff and Tran developed an optimum solution method
which takes advantage of the mathematical properties of the four module pat-
tern to reduce the number of layouts required for evaluation.

Bartholdi [5] examined the problem of scheduling a single palletizer for
two different items; he established necessary and sufficient conditions for a
zero delay schedule, developed minimizing functions of delays, and discussed
problem complexity. A somewhat different scheduling problem was studied by
Santana and Platzman [52]. For a single palletizer serving N accumulation
lanes for N types of items, they investigated the problem of determining the
best service policy to minimize the penalty rate; a penalty was charged when
a full accumulation lane caused the rejection of an arriving item, and the
service policy determined the next type of item to be served.

11. ORDER PICKING AND ACCUMULATION

The order picking problem can involve either a person or a machine traveling to each of several storage locations where items are removed from storage. Alternately, the storage location can be delivered to a stationary picking station where a person or machine removes the required items from storage.

The order accumulation problem involves a sorting of the items picked into customer groupings. The order accumulation problem also involves the unitizing of loads (palletizing) and batching of items or orders.

An order picking problem studied by Ratliff and Rosenthal [47] involves the determination of the sequence or route which minimizes the time or distance required for retrieval of a group of items (an order) from storage. Their study considered a rectangular warehouse and assumed that crossovers were allowed only at the ends of aisles. A graph theory based algorithm was developed for determining the optimum (minimum time) solution.

Goetschalckx and Ratliff [16] examined the problems of where to store items, how to sequence orders, and how to sequence items within an order. They discussed solution procedures which are appropriate for small and/or on-line computer applications.

The economic efficiency of five order picking systems was investigated by Shimizu [54]. He determined the cost per pallet and the cost per pick for the five alternatives and discussed appropriate applications for each of the alternatives.

Bartholdi and Platzman [4] have studied a number of order picking problems involving both linear storage and circular storage. The order picking problem with linear storage involves the determination of the optimum sequence

of "picks" or "visits" on the line; it has a direct computer analogy involving the sequencing of jobs stored on magnetic tape. The order picking problem with circular storage involves the determination of the optimum sequence of "picks" on a carousel conveyor which can be rotated clockwise or counter-clockwise; it has an analogy involving the sequencing of jobs stored on a disk. Bartholdi and Platzman have developed exact solutions for a single orderpicker picking items from multiple carousels, as well as bounds for heuristic procedures.

An order accumulation problem studied by Elsayed [13] involved the determination of the optimum combination of items to be included in one batch or tour. Assuming an automated storage/retrieval machine for handling, he compared four heuristic approaches for grouping items into batches. The heuristics differed only in the method of selecting the first item to be included in the batch, and tours or batches were determined by solving the traveling salesman problem. Another study of optimal batching was conducted by Armstrong, Cook, and Saipe [2]. The batching problem for a conveyorized semi-automated orderpicking system was formulated as a mixed-integer linear programming problem, and Binders' decomposition was used to solve the problem.

12. RESEARCH OPPORTUNITIES

Material handling problems, in general, are very difficult problems to solve. Performance and economic characteristics of the technological alternatives are not well understood; numerous equipment alternatives are available for consideration and the number is steadily increasing; the trade-offs inherent in choices between storage and throughput are not defined; and it is difficult to develop meaningful formulations of the optimization problems inherent in the design process.

To add to the difficulty in solving material handling problems, most of the discrete optimization problems that appear to be worthy of attention are variations of NP-complete problems. The stochastic aspects of the problem also contribute to the difficulties in obtaining useful solutions to even the simplest design problems.

However, it is encouraging to note that people in industry are developing feasible solutions to material handling problems, despite the mathematical complexities cited above. Furthermore, empirical evidence suggests they are developing reasonably good, if not optimum, solutions. The rules-of-thumb or heuristics used by material handling engineers represent a "satisficing" approach to both design and operating problems.

Because of the abilities of an experienced individual to resolve some of the more difficult combinatoric aspects of the material handling problem, the use of interactive optimization methods is receiving increased attention. Specifically, colorgraphics computer terminals are used to display outputs from simulation models and optimization models. Flexible manufacturing systems, order picking systems, automated storage and retrieval systems, and warehouse layout problems have been the subject of studies involving the use of colorgraphics computers.

Research is needed in developing large-scale models of manufacturing systems and warehousing systems. The work done on flexible manufacturing systems represents a first step in considering handling, storage, control, and processing features of a manufacturing system. Previous research on warehousing systems has failed to address the integration of receiving, in-bound inspection, movement to storage, storage, retrieval or order picking, order accumulation, movement to shipping, and shipping; storage, retrieval, and order picking

17

problems are well studied, but the other areas have received little attention.

Research contributions in other, seemingly unrelated, areas appear to be especially applicable to material handling. For example, there exists a number of opportunities to apply network and graph theoretic concepts to the formulation of warehouse layout, stock location, and order picking problems. Additionally, much of the computer science research focusing on storage and processing systems has direct application in warehousing and order picking. Research performed by technical geographers and regional scientists concerning spatial relationships may seem to be useful in the study of layout problems.

Because of the breadth of the subject of material handling, as well as the opportunities to apply results from research performed in other areas, it is not likely that a unified body of knowledge will develop that uniquely defines material handling research. Rather, it is believed that material handling will continue to provide a wide ranging number of opportunities for the application of operational research results.

REFERENCES

[1] C. C. Armour and E. S. Buffa, A heuristic algorithm and simulation approach to the relative location of facilities, Management Science 9 (1963) 294-309.

[2] R. D. Armstrong, W. D. Cook, and A. L. Saipe, Optimal batching in a semi-automated order picking system, Journal of the Operational Research Society 30 (1979) 711-720.

[3] B. G. Barrett, A further digression on the over-automated warehouse: some evidence, Interfaces 8 (1977) 46-49.

[4] J. J. Bartholdi, III and L. K. Platzman, unpublished research papers, Production and Distribution Research Center, School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, Georgia.

[5] J. J. Bartholdi, III and A. S. Rosenthal, Periodic scheduling of a materials handling system, Proceedings of the 18th IEEE Conference on Decision and Control, Fort Lauderdale, Florida (December 1979) 548-552.

[6] Y. Bassan, Y. Roll, and M. J. Rosenblatt, Internal layout design of a warehouse, AIIE Transactions 12 (1980) 317-322.

[7] W. E. Biles and E. Y. Yang, A generalized model and simulation analysis of a multiple parallel conveyor system for flexible manufacturing, 1981 Winter Simulation Conference Proceedings: T. I. Ören, C. M. Delfosse, and C. M. Shub (eds.), Atlanta, Georgia (December 1981) 391-399.

[8] Y. A. Bozer, J. S. Shieh, and J. A. White, Modeling automated storage/retrieval systems, TIMS/ORSA Joint National Meeting, Detroit, Michigan (April 1982)

[9] E. S. Buffa, G. C. Armour, and T. E. Vollmann, Allocating facilities with CRAFT, Harvard Business Review 42 (1964) 136-159.

[10] J. A. Buzacott and L. E. Hanifin, Models of automatic transfer lines with inventory banks - a review and comparison, AIIE Transactions 10 (1978) 197-207.

[11] J. A. Buzacott and J. G. Shanthikumar, Models for understanding flexible manufacturing systems, AIIE Transactions 12 (1980) 339-350.

[12] N. A. DeMars, Computer-aided warehouse layout design, 30th Annual Material Handling Short Course, Georgia Institute of Technology, Atlanta, Georgia (February 1980).

[13] E. A. Elsayed, Algorithms for optimal material handling in automatic warehousing systems, International Journal of Production Research 19 (1981) 525-535.

[14] R. L. Francis and J. A. White, Facility Layout and Location: An Analytical Approach (Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1974).

[15] S. B. Gershwin and O. Berman, Analysis of transfer lines consisting of two unreliable machines with random processing times and finite storage buffers, AIIE Transactions 13 (1981) 2-11.

[16] M. P. Goetschalckx and H. D. Ratliff, Order picking problems, EURO V/TIMS XXV Conference, Lausanne, Switzerland (July 1982).

[17] S. C. Graves, W. H. Hausman, and L. B. Schwarz, Storage-retrieval interleaving in automatic warehousing systems, Management Science 23 (1977) 935-945.

[18] S. C. Graves and B. W. Lamar, A mathematical programming procedure for manufacturing system design and evaluation, Proceedings of the IEEE Conference on Circuits and Computers, Port Chester, New York (October 1980) 1146-1149.

20

[19] S. C. Graves and D. E. Whitney, A mathematical programming procedure for equipment selection and system evaluation in programmable assembly, Proceedings of the 18th IEEE Conference on Decision and Control, Fort Lauderdale, Florida (December 1979) 531-536.

[20] G. Gregory and C. D. Litton, A conveyor model with exponential service times, International Journal of Production Research 13 (1975) 1-7.

[21] W. H. Hausman, L. B. Schwarz, and S. C. Graves, Optimal storage assignment in automatic warehousing systems, Management Science 22 (1976) 629-638.

[22] J. L. Heskett, Cube-per-order index - a key to warehouse stock location, Transportation and Distribution Management 3 (1963) 27-31.

[23] T. J. Hodgson and T. J. Lowe, Production lot sizing with material handling cost considerations, AIIE Transactions (forthcoming).

[24] J. J. Hughes, Application of simulation in the design and development of a flexible manufacturing system, Proceedings of the 17th IEEE Conference on Decision and Control, San Diego, California (January 1979).

[25] G. K. Hutchinson and B. E. Wynne, A flexible manufacturing system, Industrial Engineering 5 (1973) 10-17.

[26] E. Ignall and A. Silver, The output of a two-stage system with unreliable machines and limited storage, AIIE Transactions 9 (1977) 183-188.

[27] P. S. Jones, A Least-Cost Equipment Selection Technique for Distribution Warehouses (Stanford Research Institute, Menlo Park, California, 1971).

[28] C. Kallina and J. Lynn, Application of the cube-per-order index rule for stock location in a distribution warehouse, Interfaces 7 (1976) 37-46.

[29] Y. Karasawa, H. Nakayama, and S. Dohi, Trade-off analysis for optimal design of automated warehouses, International Journal of Systems Science 11 (1980) 567-576.

[30] D. A. Kind, Measuring warehouse space utilization, Transportation and Distribution Management 5 (1965) 22-33.

[31] D. A. Kind, Elements of space utilization, Transportation and Distribution Managment 15 (1975) 29-34.

[32] E. D. Kooy, Making better use of available warehouse space, Industrial Engineering 13 (1981) 26-30.

[33] E. D. Kooy and D. L. Peterson, Use of the computer in warehouse layout and space planning, Proceedings of the 1971 AIIE Conference. Boston, Massachusetts, 131-138.

[34] W. H. Marsh, Elements of block storage design, International Journal of Production Research 17 (1979) 377-394.

[35] J. O. Matson and J. A. White, Storage system optimization, Report No. 81-09, Production and Distribution Research Center, Georgia Institute of Technology, School of Industrial and Systems Engineering, Atlanta, Georgia (1981).

[36] J. O. Matson, J. S. Shieh, and J. A. White, Analysis and design of storage systems, EURO V/TIMS XXV Conference, Lausanne, Switzerland (July 1982).

[37] W. L. Maxwell, Solving material handling problems with OR, Industrial Engineering 13 (1981) 58-69.

[38] W. L. Maxwell and R. C. Wilson, Dynamic network flow modeling of fixed path material handling systems, AIIE Transactions 13 (1981) 12-21.

[39] D. J. Medeiros, R. P. Sadowski, D. W. Starks, and B. S. Smith, A modular approach to simulation of robotic systems, Proceedings of the 1980 Winter Simulation Conference: T. I. Ören, C. M. Shub, and P. F. Roth (eds.), Orlando, Florida (December 1980) 207-214.

[40] J. J. Moder and H. M. Thornton, Quantitative analysis of the factors affecting floor space utilization of palletized storage, Journal of Industrial Engineering 16 (1965) 8-18.

[41] E. J. Muth, Modeling and system analysis of multistation closed-loop conveyors, International Journal of Production Research 13 (1975) 559-566.

[42] E. J. Muth, A model of a closed-loop conveyor with random material flow, AIIE Transactions 9 (1977) 345-351.

[43] E. J. Muth and J. A. White, Conveyor theory: a survey, AIIE Transactions 11 (1979) 270-277.

[44] S. Y. Nof, J. L. Knight, Jr., and G. Salvendy, Effective utilization of industrial robots - a job and skills analysis approach, AIIE Transactions 12 (1980) 216-225.

[45] H. Ohta, GERT analysis of a single conveyor system, International Journal of Production Research 17 (1979) 405-410.

[46] D. T. Phillips, Simulation of material handling systems: when and which methodology?, Industrial Engineering 12 (1980) 64-77.

[47] H. D. Ratliff and A. S. Rosenthal, Order-picking in a rectangular warehouse: a solvable case of the traveling salesman problem, Report No. 81-10, Production and Distribution Research Center, Georgia Institute of Technology, School of Industrial and Systems Engineering, Atlanta, Georgia (1981).

[48] H. D. Ratliff and T. Tran, Optimum four module pallet packing, Report No. 82-03, Production and Distribution Research Center, Georgia Institute of Technology. School of Industrial and Systems Engineering, Atlanta, Georgia (1982).

[49] L. W. Rearick, F. Gudan, and J. F. Novotnak, Modeling techniques for manufacturing conveyor systems using GPSS, 1981 Winter Simulation Conference Proceedings: T. I. Ören, C. M. Delfosse, C. M. Shub (eds.), Atlanta, Georgia (December 1981) 497-504.

[50] S. D. Roberts and R. Reed, Jr., Optimal warehouse bay configurations, AIIE Transactions 4 (1972) 178-185.

[51] G. M. Sand, Stacker crane product handling system, TIMS/ORSA Joint National Meeting, Miami, Florida (November 1976).

[52] J. L. Santana and L. K. Platzman, Real-time scheduling of an "open warehouse" sorter-palletizer system, Proceedings of the 18th IEEE Conference on Decision and Control, Fort Lauderdale, Florida (December 1979) 537-539.

[53] L. B. Schwarz, S. C. Graves, and W. H. Hausman, Scheduling policies for automatic warehousing systems: simulation results, AIIE Transactions 10 (1978) 260-270.

[54] A. Shimizu, Engineering analysis of automated warehouse, Proceedings of the 4th International Conference on Automation in Warehousing, Tokyo (1981) S1-5: 1-11.

24

[55] A. Smith and P. DeCani, An algorithm to optimize the layout of boxes in pallets, Journal of the Operational Research Society 31 (1980) 573-578.

[56] H. J. Steudel, The right pallet cuts costs, Industrial Engineering 9 (1977) 14-18.

[57] H. J. Steudel, Generating pallet loading patterns: a special case of the two-dimensional cutting stock problem, Management Science 25 (1979) 997-1004.

[58] D. Stokić and M. Vukobratović, Simulation and control synthesis of manipulator in assembling technical parts, Journal of Dynamic Systems, Measurement, and Control, Transactions of ASME 101 (1979) 332-338.

[59] R. W. Swain and J. J. Marsh, III, A simulation analysis of an automated hospital materials handling system, AIIE Transactions 10 (1978) 10-18.

[60] J. A. Tompkins and R. Reed, Jr., An applied model for the facilities design problem, International Journal of Production Research 14 (1976) 583-595.

[61] A. F. Vereschagin and V. L. Generozov, Design of trajectories of operating device of automatic manipulator, Engineering Cybernetics 16 (1978) 55-64.

[62] D. B. Webster and R. Reed, Jr., A material handling system selection model, AIIE Transactions 3 (1971) 13-21.

[63] J. A. White and Y. A. Bozer, Optimum designs of automated storage/retrieval systems, TIMS/ORSA Joint National Meeting, Washington, D.C. (May 1980).

[64] J. A. White, N. A. DeMars, and J. O. Matson, Optimizing storage
system selection, Proceedings of the 4th International Conference
on Automation in Warehousing, Tokyo (1981) S4-5: 1-17.

[65] H. G. Wilson, Order quantity, product popularity, and the location
of stock in a warehouse, AIIE Transactions 9 (1977) 230-237.

[66] H. A. Zollinger, Planning, evaluating, and estimating storage sys-
tems, Proceedings of the 1975 Advanced Material Handling Technology
Seminar, Purdue University, West Lafayette, Indiana (1975).